Gearless Transmissions for Large Wind Turbines

Gearless Transmissions for Large Wind Turbines – The history and Future of Hydraulic Drives.

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Abstract:

Hydraulic transmissions are routinely used for large powers, converting high-speed rotation of electric and internal combustion prime movers to low speed rotation for driving machines where large shocks must be handled. Examples are rock crushers, sugar cane pulping mills and paper mills. If these drives were operated in the opposite sense, as is required by renewable power plant, which starts with a low-speed, irregular input and drives an electrical generator, they would provide a gearless solution for the wind turbine industry.

The traditional ruggedness and reliability characteristics which make them attractive for large power conversion in other industries could be usefully transferred to wind. More challengingly the electrical characteristics around synchronous generation and the hydraulic buffering capability of a hydraulic transmission open new design possibilities for the turbine industry. Conventional variable speed hydraulic drives already exhibit the ruggedness, weight and controllability required for large wind turbines, however hydraulic solutions generally have unacceptable efficiency at part-load; a result of the loss mechanisms internal to the pumps and motors. Artemis Intelligent Power Ltd has developed hydraulic machines, which use a different principle to off-load the unused capacity, in a manner which results in very low parasitic loss. Because of the speed at which this can be done, these machines can be controlled with a high bandwidth to follow a demand signal with good linearity and low hysteresis. Large wind turbines, in the great majority of cases, use mechanical speed-up gearboxes to couple the input rotor to a high-speed generator. Power electronics are inserted between the generator and the line frequency in order that the drive can be operated at variable speed.

Artemis will describe how applying their proprietary digital displacement technology to traditional hydraulics allows the design of an efficient, flexible, hydraulic transmission to replace the traditional gearbox, and much of the power electronics requirement for large turbines.

Introduction

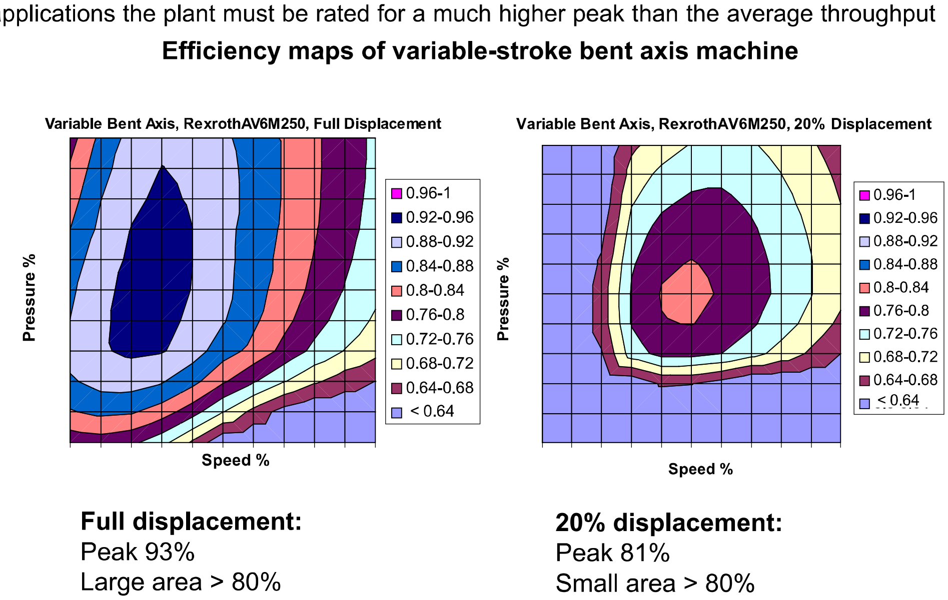
In the 1970s the world was in the grip of an energy crisis. Such was the perception of the seriousness of the situation that the then four major American car manufacturers cancelled their “pony” cars and started to build compact cars, which they could sell on the basis of low fuel consumption rather than horsepower – even with the current concern over peak-oil and global warming we haven’t yet seen a repeat of this.

Serious attention was paid to renewable energy sources for the first time in living memory, wind being a predominant focus, at least in terms of its potential for generating electricity. At that time high-power semiconductors were still exotic and expensive and so at least two of the early experimental turbines, that of Sir Henry Lawson-Tancred in Yorkshire, and the 1.3-MWe Bendix/Schachle turbine in the USA, used variable hydraulic drives. Neither made it beyond proof-of-concept stage. Since those early days there have been a few more hydraulic drive experiments, though none yet commercially successful. Gearboxes and electronic frequency converters have, since then, swept all before them. Currently 85% of all large turbines are so configured.

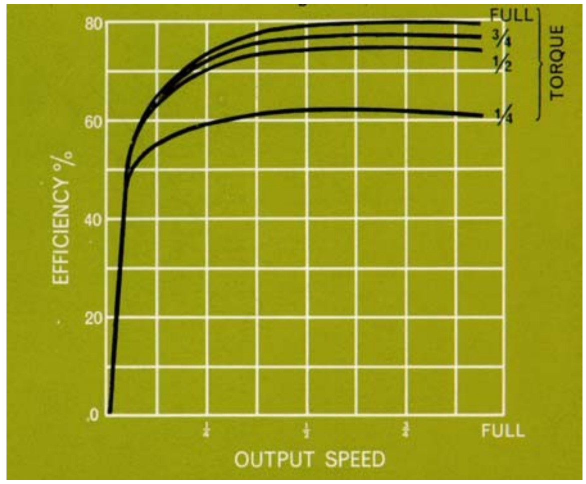
The purpose of this paper is not to argue that this competition of technologies and its outcome was in any way unfair, it is to suggest that a new form of hydraulic transmission is emerging which, perhaps, is equipped with sufficient advantage to once again upset the apple-cart.

Comparison of Digital Displacement to Conventional Hydraulic Machines

In many power transmission applications the plant must be rated for a much higher peak than the average throughput power. The loss mechanisms in conventional hydraulic machines generally do not scale down with diminishing power throughput. So, even though the peak efficiency of conventional machines can reach 95% overall, the actual machine efficiencies in operation are much lower. Figure 1 shows the full and 20% displacement efficiency maps for a typical bent-axis machine.



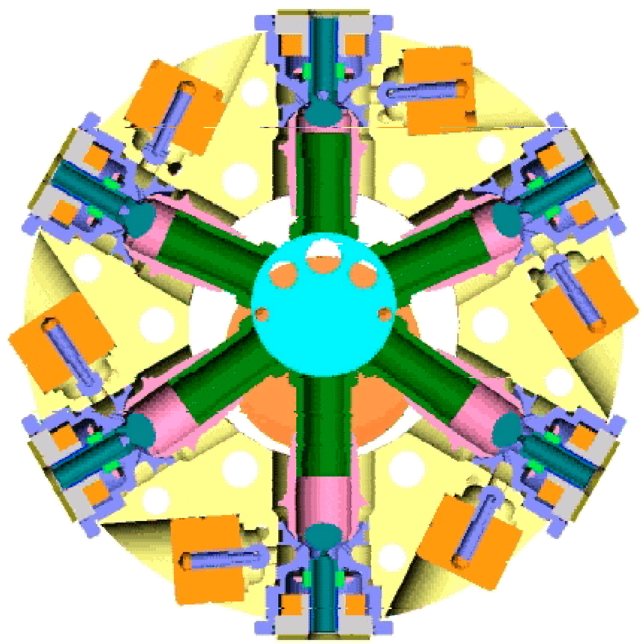
Given that fluid power systems generally have two stages of conversion, such that the part-load efficiencies of two machines must be multiplied together, the losses are too high to bear for many applications. Figure 2 illustrates a typical overall "gearbox" efficiency for a hydrostatic transmission. This level of losses has historically limited the spread of hydraulic transmissions; they are employed only where the magnitude of loss is relatively small –eg. garden tractors, or where the application requires the control, power density and/or robustness that can only be achieved with hydraulic drives.



Digital Displacement™ Hydraulic machines use a different principle to reduce output below rated flow. Like other high-power, high-pressure, hydraulics they employ reciprocating pistons and cylinders to minimise leakage, seeing as cylindrical parts stretch axisymetrically and can maintain clearances. But, instead of employing commutating ports to switch the working chambers between high and low pressure manifolds, they use poppet valves. These are not in themselves novel, but the fact that they are controlled by high-speed actuators, which can reconfigure each working chamber to pump, idle or motor on each successive stroke certainly is.

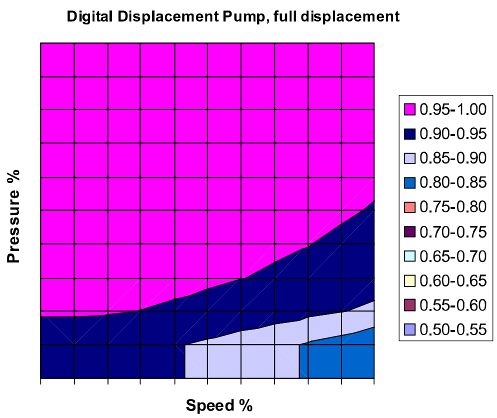
The radial configuration shown in figure 3 has been arrived at for three reasons: the piston driving eccentric is at the centre of the machine, as small as possible and therefore with the lowest surface velocity for a given shaft speed, the valves are at the outside, and therefore can be as big as needed to provide the needed flow rates with low pressure drops and, finally, the radial configuration allows banks of cylinders to be placed side-by side along the same crankshaft. This final advantage can be used to eliminate or at least reduce loads on the main shaft bearings as well as permitting machines of large capacity to be assembled from many pump modules of the same design.

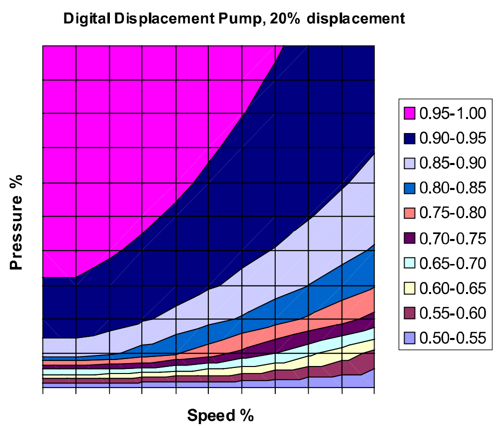
Fluid machines made in this configuration, and there are several precedents, are very difficult to improve on in terms of their outstanding mechanical efficiency. With the use of articulating cylinders, there are almost no side loads on the pistons. The principal losses are the piston foot bearing, the sliding interface between the piston and cylinder, the articulation of the cylinder and the breathing of the valves. It is very hard to see how to improve on any of these beyond small tribological tweaks and optimisation of dimensions. A working chamber under load will be converting torque on the shaft to displaced fluid as efficiently as possible.



A working chamber is said to be idle when the poppet valve connecting it to the low-pressure manifold is held open, such that both intake and pumping strokes draw and return flow at low pressure. As such the chamber is never pressurised in this mode, there is no loss from leakage or compressibility and the bearings are not loaded up to create higher levels of friction torque. The machines built by Artemis to date show idle loss powers in the range of 7 W/(litre/min).

The machines work by using a continuously varying ratio of disabled to enabled cylinders to achieve the required flow rates or power flows. Irrespective of the number of working chambers, with time averaging, effectively any level of flow can be maintained. There is no hysteresis or non-linearity in output. Typical efficiency plots are shown in figure 5. These demonstrate a very high peak level of efficiency, typically around 97%, but also have a very wide range of operation above 95%. Squaring 0.95 gives a throughput efficiency of 90%, which is comparable to that of a current wind turbine transmission, if the power electronic losses are included.





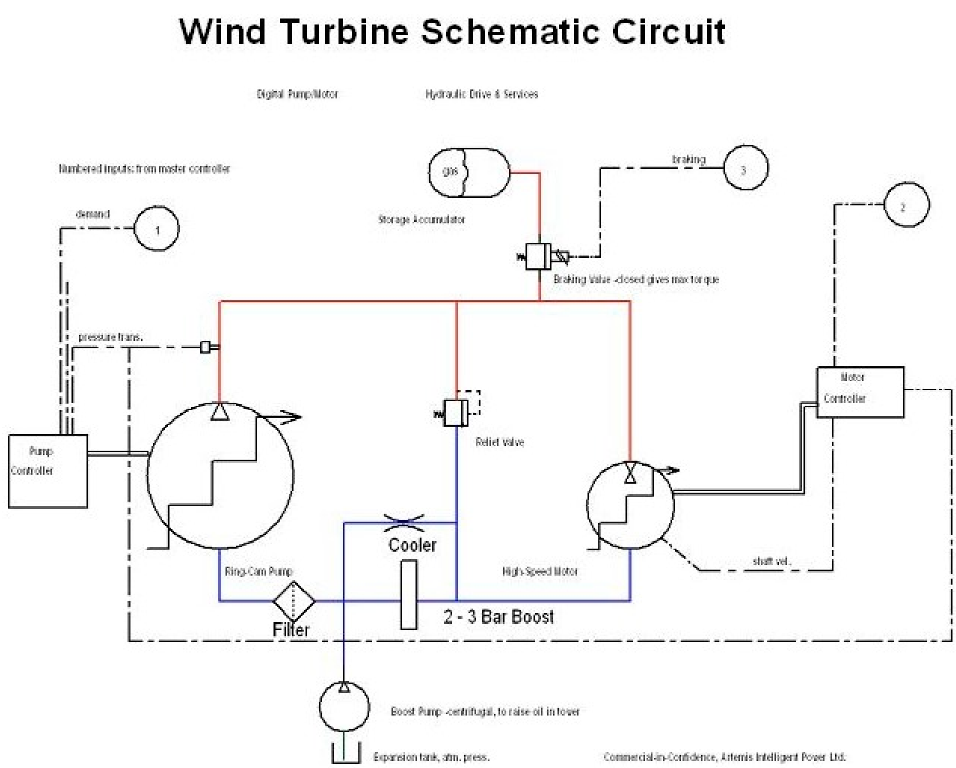
Full displacement:
Peak efficiency 97%
Very wide band

20% displacement:
Peak efficiency 96%
Wide band

Unlike conventional hydraulics, Digital Displacement™ machines are not ruled out of court because of poor efficiencies.

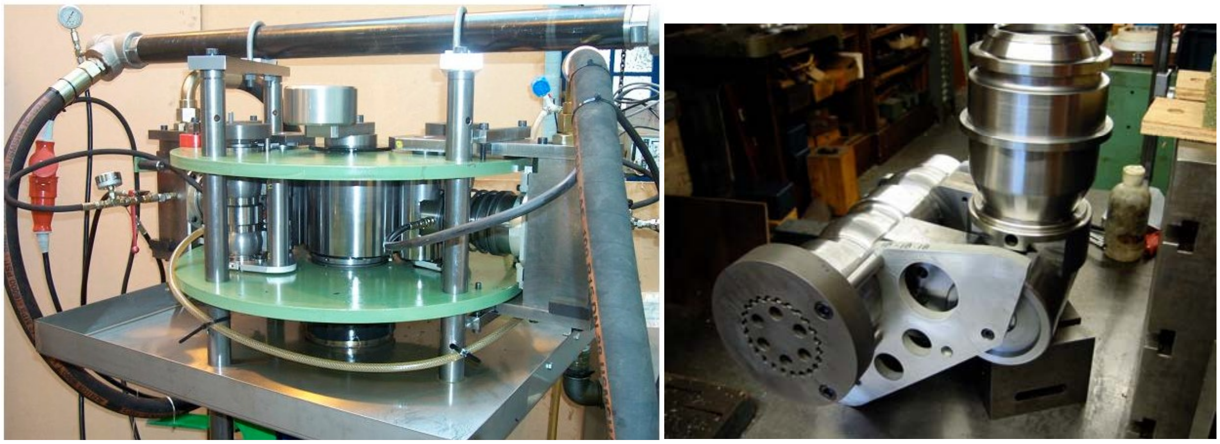
Aspects of a Digital Displacement™ Wind Turbine Installation

A wind turbine transmission can be formed from a low-speed ring-cam pump, driven at rotor speed, pumping fluid into a high-pressure manifold. A large gas accumulator can be coupled to the manifold to both store energy and decouple the input flow from the pump and the output flow to the hydraulic motors, as shown in the circuit diagram of figure 6. The motors can be driven at a constant 1500 or 1800 RPM to allow the use of synchronous generators directly linked to grid frequency. The absence of high-power electronics allows the generators to work at a considerably higher voltage, perhaps 11 kV, which in turn eliminates at least one stage of transformer and permits a considerable reduction in electrical conductor size.



The ring cam pump consists of a multi-lobed cam, mounted directly on the rotor shaft between two main bearings, and an array of pumping modules disposed radially around the main shaft such that their rollers run on the cam surface and actuate the pistons of the pumping modules. Photos of the first test rig are shown in figure 7. The number of pumping operations is the product of the number of cam lobes multiplied by the number of pumping modules, perhaps as many as a thousand cylinder actuation opportunities per revolution of the main shaft. Each of these can be selected to pump or idle on each individual stroke, giving a very tight control of the torque applied to resist the wind-driven blades. The pump response is such that it can move from full idle to maximum torque in about ten degrees of rotor rotation.

Ring Cam Pump Roller Test Rig



The kinematic arrangement used to locate and restrain the rollers and pistons allows for misalignment due to deflection of the rotor shaft, in a way that meshing gears would never permit, such that there is no foreseeable problem in integrating the main rotor shaft, its two bearings and the pump. In doing this, not only are two high-capacity, expensive, bearings and a second primary shaft eliminated, the coupling between the two shafts is also made redundant, as is any mechanical brake. This gives a weight saving of x in a 1.5 MW design.

The suggested layout of a 5 MW transmission, figure 8, shows two high-speed Digital Displacement™ motors attached directly to the pump casing. This formation permits the casing to return the relatively high flows of low-pressure oil directly as well as eliminating high-pressure hoses between the units, which could be a source of failure. Two motors are suggested in the layout in order to split the output of the turbine equally. In this way, given a load factor likely to be in the .25 - .35 region, most of the time one or other of the drives can be shut down and the consequent parasitic losses of both a motor and a generator eliminated. The fact that the machines are identical increases redundancy without seriously increasing complexity.

Characteristics of Digital Displacement™ with regard to Wind Applications

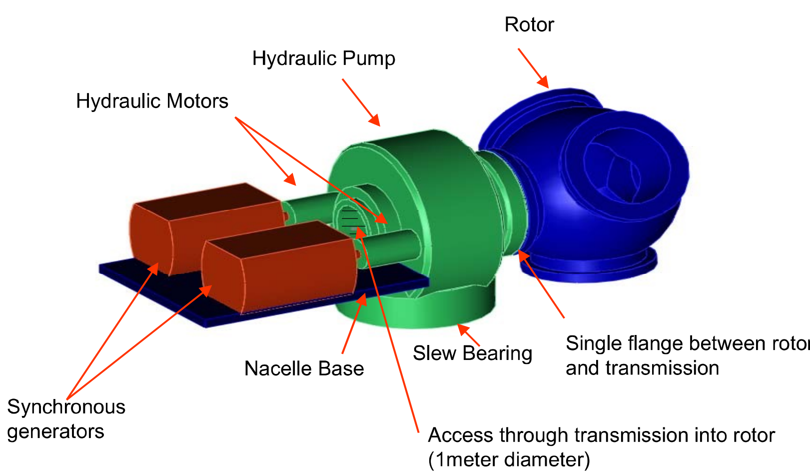
There are a number of properties conferred simply by the fact that the transmission is hydraulic. Unlike a gearbox, where the input load is spread on a very limited number contact lines, which slide as well as roll, the torque is applied to as many rolling contact lines as there are active pumping modules –perhaps 20 or more. These rolling contact lines can be as long as is required to keep the Hertzian contact stress well within indefinite life levels for the maximum operating pressure. The system pressure can be limited, by both electronic control of the pump and ultimately by the pressure relief valve, which prevents overstressing of the cam, rollers and pumping modules. The pump physically cannot be overloaded, unlike a gearbox.

Ring-cam motors are generally expected to last 40,000 hours at rated power. Those made by MacTaggart Scott are welded into the hulls of submarines for life. Ruggedness and reliability are expected.

Heat evolved through the transmission inefficiency goes directly into the oil, which can easily serve to transport it to a radiator for rejection to the surrounding air.

The power density of hydraulic machines is at least three times higher than the most advanced electric motor – a result of the limitation of flux den-

Wind Turbine with hydraulic transmission



sity in ferromagnetic materials versus the pressure limit of hydraulic machines. The integration of the pump and the rotor works to increase this weight advantage.

While the first reaction to this concept is generally to suggest that the hydraulic motor and generator could be usefully positioned at the tower base to reduce weight and improve access, it is fairly easy to establish that the mass of the pipes, coupled with the inherent flow loss, makes this a less attractive proposition than the relatively conventional arrangement shown above. With all of the major changes implicit in this transmission it is expected that a weight saving of 20% will be achieved over a conventional gearbox design.

The accumulator serves not only as an energy store but also as a decoupling means. Compared with the displacement of individual pumping or motoring cylinders it is like a vast ocean, ensuring that a stable pressure exists between the machines. This completely eliminates any resonant behaviour being passed through the driveline. These resonances are usually very destructive.

If for any reason the grid should be lost, the accumulator permits the control system to maintain stable operation and, should connection not return, enter a controlled shutdown. The generators continue to spin, the hydraulic motors are driven by occasionally enabled motoring cylinders, requiring very little flow, and the pump continues to operate and fill the accumulator whilst the rotor turns. After some time – perhaps ten seconds, depending on accumulator size – the controller could decide to shut down the turbine by some combination of blade pitching or increasing the pump torque.

Roadmap to Wind Transmission Development

Much work has already been done to get the technology to the current level. Digital Displacement™ machines are working in other applications, on-road and off-road vehicles and fan-drives at power levels up to 200 kW. The low-speed ring-cam pump technology has been built into a three module test pump with a two lobe cam, and achieves its full speed of 200 RPM and is designed to work at 400 Bar, giving a power rating of 125 kW per module.

In the immediate future a ring-cam pump, based on the test unit, will be designed and built. The complementary high-speed motor will be an up-stroked development of the current Artemis mobile machine. The two will be coupled in a ground test unit with a power rating of approximately 800 kW. Our partners TUV-NEL will host the test rig and conduct the final evaluation. This Carbon Trust aided programme should be complete within an18 month period.

After the design portion of the first programme is complete, further effort will be devoted to work on very large scale turbine transmissions in the 5 – 10 MW range.

Acknowledgements

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